DEVELOPMENT OF NEW PERFORMANCE BASED STANDARDS FOR EARTH BUILDING

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SUMMARY

As the number of houses built from earth increases in New Zealand so has the need for standards. The background, development and some key technical issues are outlined.

Three New Zealand Standards for earth building have been developed using limit state design principles. The standards are NZS 4297 *Engineering Design of Earth Buildings*, NZS 4298 *Materials and Workmanship for Earth Buildings* and NZS 4297 *Earth Buildings Not Requiring Specific Design*. The standards cover adobe (sun dried brick), rammed earth and pressed brick construction including reinforced and unreinforced walls.

No substantial performance based standards have been developed internationally so much of the approach had to be developed for these standards. The design approach is based on existing masonry and concrete standards. An energy method is used for out-of-plane seismic design of unreinforced earth walls.

Simple and low cost materials tests were adopted to establish that earth wall materials meet the building code requirements. Construction details are based on current best practice in both Australia and New Zealand. A small number of structural tests were carried out to confirm the structural strengths assumed.

EARTH BUILDING IN NEW ZEALAND

History

Earth Building began in New Zealand at the beginning of European Settlement. Although all forms of masonry lost favour after the 1846 and 1855 earthquakes. 121 earth houses still exist that were constructed between and 1840 and 1870, and a further 168 survive from 1870-1910. There was little activity until a number of houses were built of cement stabilised earth in the 1940's due to influence of Pip Alley at Canterbury University and the materials shortages that followed the war. Interest dwindled again until a significant increase in the 1980's. [1]

Current Situation

In the 1980's growing interest in more environmentally friendly and sustainable buildings resulted in increasing public acceptance of earth housing. People wanting to use natural building materials were leaders in the recent upsurge in earth building in New Zealand. Subsequently many small earth homes and large executive style houses have been constructed or are currently being constructed in New Zealand.

It is estimated that well over 100 earth buildings have been built during the past 10 years in New Zealand and this has necessitated builders and engineers liaising in detail with building authorities to establish the viability of various earth building techniques.

The earth building community has been active in gaining greater public interest and more widespread acceptance within the building regulatory system.

CONSTRUCTION TECHNIQUES

Rammed Earth

Monolithic wall panels, usually cement stabilised earth, are compacted between stiffened shutters well supported to prevent lateral spread. This technique is best suited to well graded sandy or gravelly soils. Compaction is normally done in 100-150mm layers by pneumatic tamper or hand rammers.

Adobe

Air dried "mud-bricks" made from a puddled earth mix cast into a mould. The earth mix contains sand, silt and clay and sometimes straw or a stabiliser which is also used to mortar the walls.

Pressed Earth Bricks

An earth brick that is formed in a mechanical press either machine or hand operated. A "CINVA ram" is a common hand press. Walls are usually laid with cement mortars.

INTERNATIONAL STANDARDS AND THE WRITING PROCESS

Existing Standards

There are prescriptive earth building standards in China, Peru, and Turkey. In the USA there is a brief mention in the UBC documents, there are state codes in Arizona and New Mexico and some local County codes. These standards generally are brief guideline documents that give information about overall structural form and materials with some indicative strengths.

Australia

Some rammed earth buildings constructed by English settlers still survive from the 1830's. Temporary earth buildings were used earlier to a limited extent by Australian Aborigines. [2]

In 1952 earth building gained impetus when Architect/Engineer George Middleton wrote *Bulletin 5 Earth-wall Construction* for the Commonwealth Experimental Building Station. The 2nd metricated 1976 edition was published at a time when earth building activity was increasing. The 3rd 1981 edition of this handbook included specific evaluation procedures and became the defacto standard for earth construction and was accepted by many local authorities. The current 4th edition, 1987, is 65 pages and published by the National Building Technology Centre.[3] A new handbook sponsored by Standards Australia is currently at draft stage.

The process of development of the New Zealand Standards

The development of Earth Building Standards in New Zealand began in 1991 as a project to develop guidelines suitable for New Zealand Territorial Authorities by a group of engineers and architects sponsored by the Earth Building Association of New Zealand (EBANZ). The group worked from various New Zealand Masonry, Concrete and Non-Specific Design Standards and an existing *Non-Specific Design Guidelines* [4] document. The latter document enabled earth home builders to select a rational layout with specific details to then be checked and have calculations done by a Registered Engineer. The EBANZ group further rationalised the practise of earth building for a wider range of styles and put together a draft for engineering design.

In 1994 Standards New Zealand accepted responsibility for the project which would have become the first Joint Australian New Zealand materials standard. The Australians brought in considerable breadth of experience and contributed very significantly especially in the area of materials and workmanship. The enlarged committee was rather unwieldy with over 20 members and serious differences became evident due to the less regulated Australian house construction culture.

In March 1997 the project became "de-jointed" from Australia and the New Zealand public drafts were issued August 1 1997.

NZS 4297 ENGINEERING DESIGN OF EARTH BUILDINGS

The Engineering Design Standard specifies design requirements and design methodologies for earth buildings limited to wall heights of 6.5m. Most earth buildings are small shear wall structures using floor and ceiling diaphragms and bond beams.

Earth as used in walls of buildings has a low compressive strength with large wall thicknesses generally in the range 230mm-400mm. Earthquake loads are critical for most earth buildings and this height limitation recognises the limits of the material and the current state-of-the-art in understanding modern earth buildings in seismic areas.

Seismic Zone Factor

Because of the wall height limitation the seismic zone factor Z to be used with NZS 4203 *The Loadings Standard* [5] is reduced to 0.4 for Northland. This more accurately reflects the hazard as mapped by seismologists [6] which was artificially restricted to 0.6 in NZS 4203 to minimise risk to limit damage in the event of a serious earthquake in Auckland.

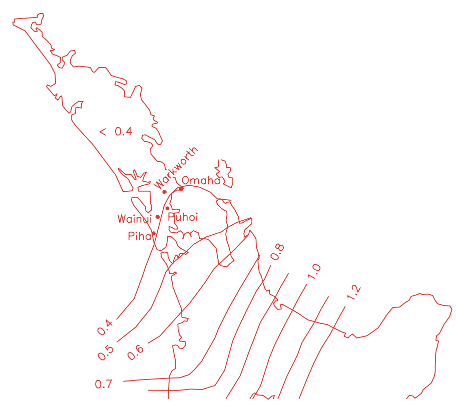

Figure 1 Seismic Zone Factor, Z, for Northland and Auckland from NZS 4297

Strength

Strength information is usually obtained from tests of the specific wall material which are specified in the Materials and Workmanship Standard.

Two grades of earth are specified within the document.

Standard Grade with a design compressive strength of 0.5Mpa which can be obtained by low strength materials with a minimal amount of testing,

or *Special Grade* which requires more testing to reasonably predict the characteristic strength. Stabilised earth may achieve test compressive strengths of up to 10Mpa. It is expected that most engineered structures would be of Special Grade.

Methodology

The design approach in the standard uses elastic and limited ductile response and is based on simple ultimate strength reinforced concrete theory. Limited ductility uses a ductility factor of 2.0 and 1.25 for the narrower Cinva bricks.

An energy method is used for assessing the ultimate limit state seismic out-of-plane resistance of walls spanning vertically. Elastic design would be based on strength at first cracking. The energy approach is based on the collapse mechanism when the displacement of the wall moves beyond stability. The method is as prescribed by the New Zealand National Society of Engineers in their document on the improvement of earthquake risk buildings.[7]

Wall Height

Unreinforced walls are restricted to 3.3m height and the maximum height to thickness ratios are as follows

	Earthquake zone factor	
	Z<0.6	Z>0.6
Unreinforced load bearing wall	10	6
Reinforced load bearing wall	16	10
Unreinforced columns	4	3
Reinforced columns	8	6
Unreinforced non-load bearing wall	12	8
Reinforced non-load bearing wall	18	12
Reinforced cinva brick	24	16

NZS 4298 MATERIALS AND WORKMANSHIP FOR EARTH BUILDINGS

Overview

The Materials and Workmanship Standard defines the materials and workmanship requirements to produce walls which, when designed in accordance with NZS 4297 or NZS 4299, comply with the requirements of the New Zealand Building Code.

General requirements are given for all forms of earth wall construction with specific requirements for the three most common forms of construction in New Zealand at present namely adobe, pressed brick and rammed earth.

Guidelines are also given for other forms of earth construction including insitu adobe, poured adobe and cob. There are successful examples of these latter methods in New Zealand but not enough work has been done to date to be able to confidently standardise all criteria. The success of these methods of construction depends on selecting a soil mix with or without stabilisers that effectively eliminates uncontrolled shrinkage cracking and on the good detailing of control joints.

Control joints are specified for all earth walls, except adobe brick walls made with mortar which does not contain cement. These joints ensure that any shrinkage cracking that does occur is at predetermined locations to maintain the wall strength and serviceability requirements. Longitudinal shrinkage is controlled by providing full height openings or vertical control joints at not more than 3.6 m centres and at changes in wall height and thickness.

Materials Testing

Earth buildings are often constructed with local soils from near the building site and detailed laboratory test results are often not available for a building project.

The Material and Workmanship Standard specifies simple low cost material tests for determining the strength, durability and construction requirements of earth wall materials together with detailed procedures, testing frequencies and required results. It is recommended in the Standard that testing, wherever possible, takes place on the building site and under the direction of the person responsible for the construction of the walls. This testing can be done in the presence of the owners or controlling authority as required.

Strength Tests

Compression or modulus of rupture tests are specified for determining the strength requirements of the earth wall materials. Samples for these tests comprise of 5 or more individual specimens. For standard grade construction, with a design strength of 0.5 Mpa, the required test results for the least of the 5 individual results in the set are as follows:

- compression test for sample with height /thickness ratio of 1.0 — 1.3 Mpa
- compression test for sample with height /thickness ratio of 0.4 — 1.8 Mpa
- flexural tensile test — 0.25 Mpa

Adobe and pressed bricks made in New Zealand typically have a height to thickness ratio of between 0.4 and 0.5. As a comparison with overseas practice, the *New Mexico Building Code* 1991 [8] specifies that one sample out of five adobe bricks shall have a compressive strength of not less than 250 pounds per square inch (1.725 Mpa).

Aspect ratio correction factors are provided in the standard.

Any compression tests need to be done in a laboratory

but a simple field test procedure is detailed for the modulus of rupture test.

Flexural tensile strength as measured by modulus of rupture is very variable with most results lying between 10% and 20 % of the compressive strength. The ratio also varies depending on whether the bricks are adobe, pressed, stabilised or unstabilised. Very few results lie outside 30%, so a compressive strength multiplier of 3.5 times modulus of rupture, based on unstabilised adobe, was adopted as a conservative benchmark for all materials.

A brick drop test is specified for simple field testing of bricks during construction. Experience in New Zealand and overseas has shown that bricks passing the drop test pass the other strength test requirements for standard grade construction.

Durability Tests

The pressure spray erosion test or the Geelong method drip erosion test are specified for assessing the durability characteristics of earth wall materials. The pressure spray test is an aggressive procedure developed by the former National Building Technology Centre of Australia, and the drip erosion test was developed at Deakin University, Australia.

The durability of materials is assessed in terms of erodibility indices which are used in NZS 4299 for determining the minimum eaves widths for buildings in different wind zones and degrees of wall exposure.

The erodibility indices for the two methods are shown below :

Erodibility Index	Spray Test Depth (D) (mm/hr)	Erosion Test Depth (d) (mm)
1	<20	Not applicable
2	20<D<50	0<d<5
3	50<D<90	5<d<10
4	90<D<120	10<d<15
5 (Fail)	D>120	d>15

An erodibility index of 1 is to be determined only by the pressure spray test.

A wet dry appraisal test is also specified to eliminate unsuitable earth building materials which may be able to pass strength and other durability tests, but because of the clay minerals present or because of in appropriate mix constitution or manufacturing techniques, are likely to fail in service after repeated wetting and drying. The test simulates a number of wetting and drying cycles.

A shrinkage test is specified with a maximum of 0.05% for rammed earth, 1.0% for mortar with cement and 3.0% for mortar without cement.

A moisture test is specified for rammed earth and a layering test for pressed bricks.

Statistical Approach

The appropriate statistical distribution and the coefficient of variation (C_v) are important when determining any characteristic strength. Soils used in earth building are very variable but the compressive strengths of dried or compressed earth materials usually have a C_v between 0.15 and 0.3. No sets of test data large enough to reasonably determine the underlying population distribution were located. The C_v was determined from several series of 20 to 30 results. The Australian Masonry Standard AS3700 [9] nominates a method for determining the characteristic strength that requires 30 specimens to be tested to determine the C_v and from this the characteristic strength. This is not viable due to the time and effort to construct specimens and the cost of testing for a simple house construction. A 5 specimen simplified approximation was used to determine the characteristic strength

$$f' = \left(1 - 1.5\frac{x_s}{x_a}\right)x_1 \tag{1}$$

Where x_1 is the lowest of the five results, x_s is the standard deviation and x_a is the mean.

The standard also provides the more reliable Ofverbeck Power Method [10] for sample sizes of 10 to 29. This method, which is presented in a simplified form, is not dependant on knowing the population distribution to determine the characteristic strength.

NEW ZEALAND STANDARD 4299 NON-SPECIFIC DESIGN OF EARTH BUILDINGS

Overview

The Earth Buildings not Requiring Specific Design Standard sets down the design and construction requirements for adobe, pressed earth brick and rammed earth buildings not requiring specific design by an engineer and is intended to be approved as a means of compliance with the relevant clauses of the New Zealand Building Code. It is the earth building equivalent of NZS 3604 the 300 plus page *Code of Practice for Light Timber Frame Buildings not Requiring Specific Design* [11], but with its scope limited to foundations, floor slabs and walls.

Buildings covered by the standard are restricted to those with single storey earth walls and light or heavy timber framed roof or with single storey earth walls and a timber first floor, timber walled second storey and a light timber framed roof.

Earth wall heights are restricted to a maximum of 3.6 m where the earthquake zone factor is equal to or less than 0.6 and to a maximum of 3.0 m where the earthquake zone factor is greater than 0.6.

Unreinforced earth walls where the earthquake zone factor is greater than 0.6 are not within the scope of the standard.

Durability

An earth wall is deemed to comply with the durability performance criteria if, provided normal surface maintenance has been carried out, its thickness has not decreased by more than 5% nor by more than 30mm at any point during the 50 year building life. The performance of many existing earth buildings in New Zealand more than 100 years old shows that this can easily be achieved provided that the buildings are well designed with appropriate eaves widths and are well constructed. An eaves width of 600 mm is the recommended minimum in this standard with more detailed requirements provided in the standard for different wind zones, wall exposures, eaves heights and widths up to 2400 mm and for areas with up to 2000 mm per year average rainfall.

Key Structural Features

The design for earthquake loading is always more critical than the design for wind for the wind exposure limitations of the standard.

The earth walls were designed as spanning between the reinforced concrete foundation at the bottom of the wall and the top plate or bond beam at the top of the wall. Loads from tops of walls, roofs and timber second storeys were assumed to be distributed by concrete or timber bond beams or structural ceiling or roof or first floor diaphragms to transverse earth bracing walls.

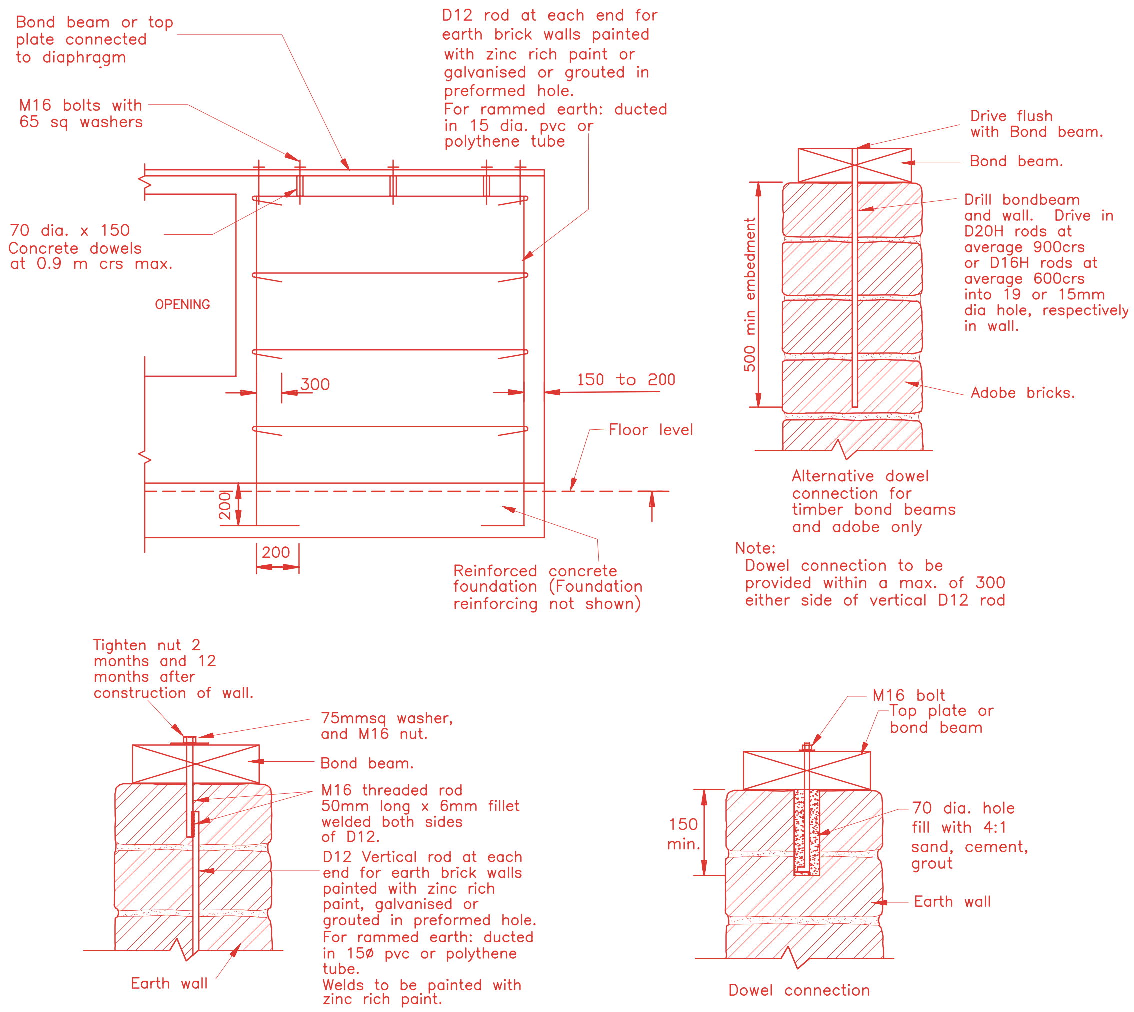

Figure 2 Reinforcing and dowels for reinforced earth walls (rearranged from fig 5.4 NZS 4299)

Two earthquake zones with the following factors were adopted for the determination of seismic loads:

Earthquake zone factor < 0.6, Z =0.6,
Earthquake zone factor > 0.6, Z =1.2.

All earth walls for earthquake zone factor < 0.6 may be reinforced or unreinforced. All earth walls in earthquake zone factor > 0.6 shall be reinforced.

The reinforcement enables smaller seismic design

loads, when a planned ductile failure mode is designed into the structure. The designed failure mode is in plane bending of earth bracing walls with yielding of vertical reinforcing at each end of the wall. Shear failure of these walls must be prevented by use of horizontal reinforcing generally.

The structural ductility factor was taken as 1.0 for unreinforced earth walls and 2.0 for reinforced earth walls.

The seismic coefficients for the design of the earth walls were as follows:
- Unreinforced earth walls with elastic response for earthquake zone factor < 0.6 C = 0.322
- Reinforced earth walls with limited ductility for earthquake zone factor < 0.6 C = 0.197
- Reinforced earth walls with limited ductility for earthquake zone factor > 0.6 C = 0.394

The design compressive strength of the earth wall materials was taken as 0.5 Mpa except for the cement stabilised cinva bricks which was taken as 2.0 Mpa.

The shear strength of earth was taken as zero for limited ductile seismic loading and as 0.09 Mpa for seismic loading with elastic response.

All earth buildings covered by the standard are braced by earth bracing walls in each of the two principal directions of the building to resist horizontal wind and earthquake loads.

A methodology and detailed tables in terms of bracing units are provided in the standard for determining the bracing required for a building and the bracing provided.

Many drawings of construction details, which have been proved in the New Zealand setting in earth buildings constructed during the past 10 years, are included in the standard.

Figures 2 and 3 (5.4 and 5.5 DZ 4299) show some typical details for reinforced earth walls.

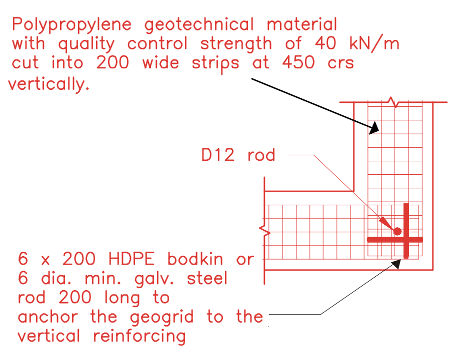

Figure 3 Option for horizontal reinforcement of reinforced walls

The bracing capacity provided by a 2400 mm long, 2400 mm high and 280 mm thick reinforced earth wall with typical details as per the above figure was calculated to be 30 kN.

The bracing capacity provided by a similar sized unreinforced earthly for earthquake zone factor < 0.6 was calculated to be 10 kN.

The energy method proposed by the New Zealand National Society for Earthquake Engineering for the strength assessment of unreinforced masonry buildings [7]was used for checking the performance of unreinforced earth walls under out of plane seismic loading. Unreinforced earth walls for earthquake zone factor < 0.6 were found to be satisfactory for the maximum wall heights specified in the standard. For example the failure of a 3000 mm high and 280mm thick wall was calculated to occur at 135 % of the calculated demand requirement with ϕ=0.6.

In reinforced earth walls vertical reinforcing supports wall panels against face loading.

STRUCTURAL TESTING

Adobe Panels

Adobe as used in walls is a low strength material with a low stiffness. Diagonal compression tests of small 1.2m adobe panels were used to investigate the effectiveness of different reinforcing approaches.

Two 1.8m high panels one 1.8m wide and the other 1.2m. In-plane test panels horizontally loaded at the top edge demonstrated some advantages of the low stiffness and sliding in the mortar layers giving effective ductile performance. The measured maximum cyclic shear strengths were 65kPa for the 1.8m wall (retested after a reinforcing rod pulled out of the foundation) and 90kPa for the 1.2m wall as reported in more detail by Morris. [12]

Rammed Soil-cement Panels

Two rammed earth panels were constructed with soil-cement compacted to approximately 100mm thick layers within the formwork.

The soil was about 5% clay, 40% silt and 55% sand, The Liquid Limit and Plastic Index varied from LL 43 and PI 17 to no measurable plasticity. The soil Proctor optimum moisture content was 27-28% which reduces with the addition of cement.

The Loading Systems

The wall panels were loaded in two directions by a double acting hydraulic actuator. The load was shared between the top face of the wall and a plate at the top edge of the wall to represent the load transmitted from other parts of the building and that from body forces within the panel itself. The load sharing was calculated to simulate a single storey house.

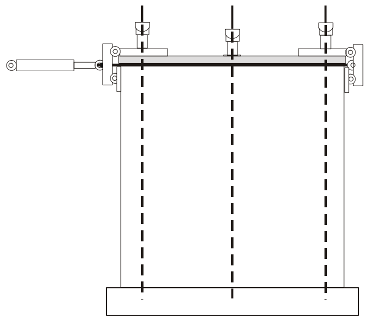

Figure 4. Schematic Diagram of Wall A showing the load system.

Wall Panel A

The first wall panel was 250mm thick 1.8 long and 1.8m high. It was constructed onto an existing foundation beam, a nib of 250 width was cast on top of the base fixed with dowels epoxy grouted into the existing concrete. The wall was reinforced with two 20mm and one central 16mm high tensile reinforcing rods (430MPa nominal yield strength).

The soil was sieved and the moisture content adjusted for optimum compaction and mixed with 10% cement by dry weight.

The wall was constructed and then a timber bond beam placed on top. The rods were pretensioned through the bond beam by tightening end bolts against a load cell. Figure 4 shows the layout of the wall and foundation.

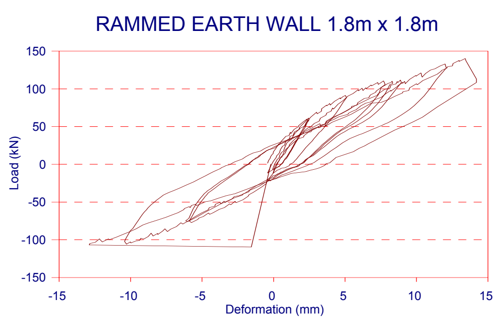

Figure 5 Cyclic load deformation results for wall A, 1.8m x 1.8m (Base failure occurred in one direction)

The nib on the foundation beam for wall A failed due to inadequate bond of the epoxy dowels. Unfortunately the full strength of the wall was therefore not measured but would have exceeded the measured maximum of 130 kN. This corresponds to a shear strength of the soil-cement of 241 kPa over the wall length.

Wall Panel B

Wall panel B was 300mm thick, 1.8m long and 2.4m high with two 20mm 430MPa reinforcing rods placed 150mm from each end of the wall. A 200mm deep concrete bond beam reinforced with two 16mm deformed rods was poured on top. The bond beam was ducted at the position of the vertical rods to allow for shrinkage. Pretension was applied to the rods and a larger foundation beam was used.

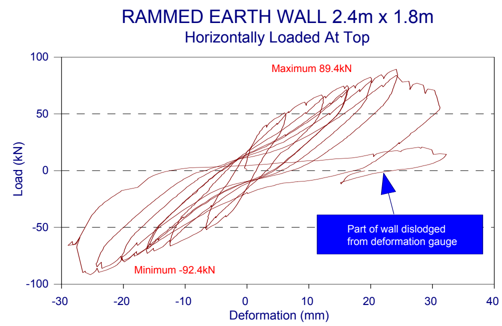

Figure 6 Cyclic load deformation results for rammed earth wall B, 2.4m x 1.8m

The second wall test proceeded well although the final failure was brittle diagonal tension. It was intended to follow the standard loading sequence proposed by Park [13] however the initial estimate of ductility was not accurate. The complete test sequence is shown in figure 6.

The performance up to failure was satisfactory with steel yield evident. Wall B carried higher loads although the quality of the rammed soil cement appeared to be lower. The height of the wall was larger and the load carried was subsequently lower at about 90kN. This is an equivalent shear strength of 143kPa. Although substantial cracking occurred, the final failure occurred suddenly with one large diagonal tension crack.

Adobe walls behave in a ductile manner require the designer to take advantage of most available walls for bracing strength. Rammed earth reaches higher strengths but reinforcement is required to prevent brittle failure.

THE POTENTIAL AND CONCLUSIONS

This new suite of standards for earth buildings extends the range of structural design and construction standards to cater for the growing interest in earth building to provide more environmentally friendly and sustainable buildings

Limit state design principles and current state-of-the-art knowledge of the design and construction of earth buildings from New Zealand and overseas. The development of these new performance based

standards for earth building has backed up by some structural testing of near full scale earth wall panels.

These standards will help prospective builders in earth in New Zealand achieve safe, durable, weatherproof, earthquake resistant and more cost effective buildings. This will simplify the process for building consent applications.

These are the first performance based standards for earth building in the world and have the potential to provide the basis for the development of similar performance based standards for earth buildings in other countries, particularly seismically active areas.

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Figures 1, 2 and 3 are used with permission of Standards New Zealand.

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